Condition Monitoring and Its Effect on the Insurance of New Advanced Gas Turbines

by

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Abstract

Insurers of new advanced gas turbines are concerned with the risk of equipment failure. The increased power levels, firing temperatures, and complexity of the new designs coupled with unvalidated analytical models and unproven service operation makes current and new advanced gas turbines a significant concern to insurers. Actions taken to reduce the probability and/or consequence of failure through condition monitoring, health trending and inspection techniques can potentially reduce risk. An insurer's view of advanced gas turbine technologies and what condition monitoring systems can do to reduce the risk of new advanced turbines is provided.

1. Introduction

The insurance industry concerns itself with the risks of equipment failure. For advanced gas turbines, the frequencies of failures and the severity of failures are major concerns. In engineering terms, however, risk is better defined as *Risk = Probability of Failure x Consequence of Failure*, where the consequences of failure include the repair/replacement costs and the lost revenue from the downtime to correct the failure. Actions taken, which reduce the probability and/or consequences of failure, tend to reduce risk and generally enhance insurability. Because of the high risks associated with insuring gas turbines, demonstrated successful operation is important to the underwriting process. If insurance underwriters consider the equipment risks to be adverse, the availability of insurance coverage may be limited or the policy terms and conditions may be adverse (i.e., high deductibles). In the next sections, a insurer's view of new advanced turbines and their technologies, condition monitoring technologies, and condition monitoring system design requirements for insurability will be discussed.

2. Risk View of New Advanced Gas Turbines and Their Technologies

The benefits of advanced gas turbines and their technologies are easily quantified. The gas turbines produce more power, use less fuel, provide higher combined cycle efficiencies, and reduce emissions levels significantly. So why is the insurance industry concerned? Because, when you step back and examine where new turbines are today versus where they were previously, there is a significant down side. In particular:

- New advanced turbines are run at higher firing temperatures, are physically larger in size, have larger throughput (airflows and fuel flows), and have higher loadings (pressure and expansion ratios, fewer airfoils, larger diameters) than previous gas turbine designs.
- The technologies (design, materials, and coatings) required to achieve the benefits are more complex to concurrently meet gas turbine performance, emissions, and life requirements.
- The design margins with these technologies tend to be reduced or unvalidated. While analytical models may be extrapolated to evaluate the new designs, full-scale verification of the new designs is an absolute necessity. Similarly, the materials being used are either relatively new or are being pushed to new limits.
- There is no reliability record for the new designs. While component rig testing (scale or sector) may help validate some component's performance, the first time the unit reaches design conditions is in the owner's plant. Essentially, the units are considered

prototype or unproven designs for the first three years of operation or until all the major design problems are identified and corrected.

- The cost of hardware and subsequent cost of ownership have increased due to the complex designs, increased size, and higher throughput in the advanced machines.
- Gas turbine operation has similarly become more complex and computer driven requiring new/different skill sets for staffing in plants.

When several of the major characteristics of advanced gas turbines are examined from a risk viewpoint (i.e., probability and consequences of failure), there are no characteristics which reduce the probability of failure and/or decrease the consequence of failure. These are summarized in Tables 1 through 3 for compressors, turbines, and combustors. The first column represents previous gas turbine designs, the second column represents new gas turbine designs, and the last column indicates the change in risk (∩ represents higher) for the design differences. Most of the comparisons are self-explanatory. The trends for compressors are towards fewer, thinner, larger 3D/CDA shaped airfoils with smaller clearances and higher pressure ratios (Rc). There are also trends towards water injection at the inlet or between compressor sections which will likely affect airfoil erosion life. The smaller clearances and high pressure ratios tend to increase the probability of encountering rubs. Design margins are set by Finite Element Modeling (FEM) at the element level which results in lower safety margins than previous designs. The costs of these larger, thinner, less-rub tolerant, and more twisted-shape airfoils are usually higher.

Table 1 - State of Gas Turbine Technology - Compressors

Previous Designs	New Designs	Risk
• 2D double circular arc or NACA 65 profiles	• 3D or Controlled Diffusion Airfoil (CDA) profiles	∩
• Large number of airfoils	• Reduced airfoil count	∩
• Repeating stages/shorter chords	• Stages unique/longer chords	∩
• Large clearances	• Smaller clearances	∩
• Low/modest pressure ratios (Rc)	• Much higher Rc's	∩
• Thicker leading edges	• Thinner leading edges	∩
• Dry operation	• Wet operation	∩
• Bulk safety margins	• Safety margins by FEM	∩
• Lower costs	• Higher costs	∩

The trends for turbines are similar with fewer, larger, 3D airfoils with smaller clearances and higher expansion ratios (Re) being used. For the early stages of the turbine, complex multi-path serpentine cooling designs are utilized. Higher strength directionally solidified (DS) or single crystal (SC) materials coupled with oxidation resistant coatings and/or thermal barrier coatings (TBC) are required to meet turbine life requirements. Design margins are set by FEM at the element level, but the long-term creep strength characteristics of the turbine materials are not well-defined. In addition, the turbine materials utilized typically have reduced temperature margin to melting as compared to previous designs. As with compressors, the smaller clearances and higher expansion ratios associated with the new design turbines tend to increase the probability of encountering rubs. The costs of these larger, complex-cooled, more twisted-shape airfoils with more sophisticated materials and coatings are substantially higher per airfoil stage.

<u>Table 2 - State of Gas Turbine Technology – Turbines</u>

Previous Designs	New Designs	Risk
• 2D reaction-type airfoil profiles	• 3D airfoil profiles	∩
• More airfoils/shorter chords	• Fewer airfoils/longer chords	∩
• Larger clearances	• Smaller clearances	∩
• Low/modest expansion ratios (Re)	• Much higher Re's	∩
• Uncooled/simple cooling designs	• Complex cooling designs	∩
• Equi-axed castings	• DS and SC castings	∩
• Oxidation coatings and/or TBC used for extending life	• Oxidation coatings and/or TBC needed to meet life	∩
• Bulk safety margins	• Safety margins by FEM	∩
• Margin to melting larger	• Margin to melting smaller	∩
• Lower costs/stage	• Ultra-high costs/stage	∩

The trends for combustors are driven by the desire for reduced emissions. The typical stable, simple, diffusion flame combustor has been replaced with barely stable, staged-combustion systems with multiple injection locations which vary with gas turbine load. This combustion system has to be monitored and tuned precisely for stability from starting to full load while maintaining low emissions and avoiding flashback and high pressure pulsations which could damage combustor and turbine components. The management of air in the combustion process and for cooling of the combustor is particularly critical so that dry low NOx (DLN) combustors have complex combustor mechanical, cooling, and TBC coating systems to provide adequate life for both can and annular combustion systems. The fuel nozzles are more complicated and larger in number due to the multiple injection locations. When dual fuel is involved or water injection is used to further reduce emissions, the purge systems for the multiple injection points are complex and can be a significant source of problems with fuel nozzle plugging and localized hot section damage. As with new design compressors and turbines, the costs of these complex combustion systems are high.

The risks and costs of these new design technologies present real problems for insurers, OEMs, and owners. Insurance is mandatory for new projects and well as for subsequent ownership and commercial operation. However, with no track record of the designs to quantify risk for insurance, investors, cost of ownership, etc., handling of the risk is difficult during the first three years of operation, i.e., until the design is proven. Insurer's appetite for new designs is limited. These reflect one-of-kind, prototype designs with few spares that can only be validated at the owner's site. Insurers typically cover sudden and accidental damage and do not want to insure design deficiencies. When these designs are insured, the insurers try to spread the risk to other insurers and re-insurers to minimize the amount of potential loss.

Table 3 - State of Gas Turbine Technology - Combustors

Previous Designs	New Designs	Risk
• NOxious, high emissions	• Very low emissions on gas	∩
• Diffusion flame with stable combustion	• Premix/DLN with instability (pulsations)	∩
• Single injection points/fuel nozzles simpler	• Multiple injection points/fuel nozzles more complex	∩
• Simple operation with simple controls	• Staged operation with complex controls/tuning	∩
• Combustor construction/cooling designs simpler	• Combustor construction/cooling designs complex	∩
• Combustion thermal life long with or without TBC	• TBC required but life reduced from flashback/distortion damage	∩
• Dry, water, and steam injected	• Dry and wet injected	∩
• Low costs	• High costs	∩

Historically, the insurers reaction to accepting risk is dependent upon industry experience. For the later "F " and "G" technology designs, the early reliability experience has been poor. There have been problems with all designs: failure and/or major rubs of compressor blades and vanes; oxidation damage and failure of turbine airfoils and coating systems; and flashback, pulsation, distortion and/or failure of DLN combustors, control systems, and transition sections. Figures 1 through 3 show typical examples of compressor, turbine, and combustor damage with this technology generation of gas turbines. This experience causes insurers to view new technology gas turbines as having little credibility.

Figure 1 – Failed Compressor Blades

Figure 2 – Failed Turbine Blades

Figure 3 – Combustor Overheating/Flashback Damage

3. Condition Monitoring Technologies

The current state of condition monitoring technologies for advanced gas turbines, from an insurance perspective, has not been particularly effective. In particular:

- Vibration monitoring – These systems were initially used proactively to determine changes in vibration and health of the turbine rotor system. This still is done in the chemical, oil, and gas industries. In the power generation industry, it has been relegated to essentially control room wallpaper or monitor displays where it may get attention only when alarm levels are reached.

- Pulsation monitoring – These systems came into being when high levels of combustor pulsations were encountered with the predecessors of today's dry low NOx (DLN) systems. Now pulsation monitoring is an absolute necessity for tuning and operating DLN systems.
- Performance monitoring – These systems were used by some to determine the amount and source of deterioration in their machines as well to determine water washing frequencies. Now, the only concern seems to be lost power (MW's) and emissions levels (regulatory requirement).
- Trend monitoring – In conjunction with performance monitoring, these systems and their associated software were designed for proactive monitoring of changes in critical machine parameters (temperatures, pressures, flows, vibration, etc.) and to alarm when a specified change in value occurred. Now, the systems and software are installed, but they are not used until after-the-fact troubleshooting of a problem.

In general, the improvements have tended to be reactionary to problems and not proactive to detect a change in equipment health or to prevent/minimize a failure. Fortunately, some new technologies have emerged from smaller companies that provide real improvements. We have supported testing of their products or had discussions on defining what their products should do. These include:

- Wave energy monitoring (Swantech) – Principally the system characterizes the structureborne noise signature of components to detect changes in component health and wear with time. This system has been tested successfully on motors, mechanical press shafting and gears, gearboxes, and rotating equipment with anti-friction and journal bearings.
- Balanced charge cleaning of oil/fuel (MAG Systems ISOpur) – This system principally charges contaminants in lube or fuel oil, cause the charged particles to combine, and then removes them from the fluids. The process actually removes contaminants from the wetted surfaces of tanks, sumps and piping with time.
- Real time IR/XRF condition monitoring of oil (Foster-Miller, Others) - These systems utilize infrared (IR) or X-Ray fluorescence (XRF) for monitoring of flowing oil systems to determine the type of contaminants and/or elements (wear particles) in the oil.
- Age/creep fatigue monitoring of airfoils (JENTEK Sensors) - Their advanced inspection technologies have a demonstrated credibility in several industries in detecting fatigue damage as well as detecting turbine coating/substrate problems. While these problems are hot topics today, ultimately turbine blading will be failing due to creep rupture and overshadow coating/substrate issues. As such, concerted efforts to quantify in-service creep damage beyond visual and blade measurement changes will become increasingly important.

The bottom line is that technologies levels incorporated into advanced turbines have not carried over to condition monitoring capabilities or in-service condition assessments.

4. Insurer's Design Requirements for Advanced Condition Monitoring System

For condition monitoring to be of mutual benefit to insurers, OEMs, and owners, the systems have to do more. From this insurer's perspective, the design requirements for an advanced condition monitoring systems should include the following:

a. The system has to be integrally designed and validated with the advanced gas turbine from the very beginning.

b. Measurements taken and inspection capabilities provided for the system need to be proactive and fundamental in detecting health changes in critical components and/or sections.

c. The system design and instrumentation needs to be both simple and reliable. Recognizing that the advanced gas turbine environment can be unfriendly to instrumentation, the use of retractable probes and instrument isolation techniques will most likely be required.

d. The primary function of the system should be to advise the owner/operator of health changes in the turbine and to initiate mitigating or corrective actions to prevent damage.

In addition to the basic design requirements for an advanced condition monitoring system, there needs to be a fresh look (i.e., out of the box thinking) of how systems should be designed and what they should be capable of doing. Some suggestions include:

1. Use embedded sensors/probes to enhance problem detection
2. Spectral analysis vibration monitoring of the gas turbine, critical blade rows, and combustion system
3. Time at temperature or creep rupture life monitoring
4. Critical airfoil temperature monitoring for loss of cooling or TBC coating
5. Blade tip clearance monitoring in critical compressor and turbine stages to prevent/minimize rubbing
6. Discrete performance monitoring and trending (i.e., detect problem areas in compressor, turbine, combustor)
7. Remote video/IR borescoping and sound analysis spectral monitoring

Including an advanced condition monitoring system as part of a new advanced turbine program will add cost to both the development and acquisition costs of new system. Given the costs of failures and problems to industry insurers, OEMs, and owners, the additional costs should be small preventive investments as compared to cost of unmitigated damage and unscheduled repairs to advanced turbines.

5. Conclusions/Closure

In summary, more sophisticated condition monitoring systems are a necessity for advanced gas turbine systems. The systems need to provide a broader range of proactive inspection capabilities and condition based measurements for the owner/operator. The systems also need to detect problems and deterioration and provide protection to prevent or mitigate damage to very high cost equipment. Under these conditions, insurers will take a positive view of advanced turbines when they have a risk-reducing, condition monitoring system.